Spherical Primary Optical Telescope (SPOT): An Architecture Demonstration for Cost-effective Large Space Telescopes

Lee D. Feinberg
Code 443
NASA Goddard Space Flight Center
Greenbelt, Maryland 20771
301-286-5923
Lee.D.Feinberg@NASA.Gov

John Hagopian, Jason Budinoff, Bruce Dean, Joe Howard
NASA Goddard Space Flight Center
Greenbelt, Maryland 20771

Abstract— This paper summarizes efforts underway at the Goddard Space Flight Center to demonstrate a new type of space telescope architecture that builds on the rigid, segmented telescope heritage of the James Webb Space Telescope but that solves several key challenges for future space telescopes. The architecture is based on a cost-effective segmented spherical primary mirror combined with a unique wavefront sensing and control system that allows for continuous phasing of the primary mirror. The segmented spherical primary allows for cost-effective 3-meter class (e.g., Midex and Discovery) missions as well as enables 30-meter telescope solutions that can be manufactured in a reasonable amount of time and for a reasonable amount of money. The continuous wavefront sensing and control architecture enables missions in low-earth-orbit and missions that do not require expensive stable structures and thermal control systems. For the 30-meter class applications, the paper discusses considerations for assembling and testing the telescopes in space. The paper also summarizes the scientific and technological roadmap for the architecture and also gives an overview of technology development, design studies, and testbed activities underway to demonstrate its feasibility.

TABLE OF CONTENTS

1. INTRODUCTION

NASA's first large space telescope, the Hubble Space Telescope, used a monolithic aspheric primary mirror in low earth orbit with an enclosed light baffle. This approach was not easily scaleable because of launch shroud mass and volume limitations. Thus the current generation space telescope, the James Webb Space Telescope, makes use of a segmented aspheric primary that is passively stable. Key challenges of the current generation space telescope are the cost and schedule associated with fabricating the primary mirror and the cost and complexity of a passively stable architecture. These limitations make it difficult to implement the architecture both in thermally varying environments and when larger and thus costlier systems are needed. The aspheric segments are also complex to test and align which drives both cost and schedule. Thus, our team is working on a next evolutionary step called the Spherical Primary Optical Telescope (SPOT), aimed at addressing these challenges. The architecture is based on an active center-of-curvature wavefront sensing and control system that eases backplane stability requirements. It is also based on replicated mirror technology that will enable both more cost-effective Hubble class primary mirror sizes and will also enable a feasible path to much larger apertures that will be needed in the future. The center-of-curvature wavefront sensor and adequate mirror degrees of freedom provide an approach to both test and actively align the system in space. This can enable lower testing costs on the ground and aperture sizes larger then can be tested on the ground. The basic architecture will result in both lower cost Hubble-size apertures and eventually extremely large primary mirror architectures.

2. Science and Technical Drivers

Our team envisions the first applications of the SPOT technology to be aimed at the least ambitious applications: laser based receivers for LIDAR and communications. Current LIDARs, such as GLAS and CALIPSO, use single primary mirror receivers that are only 1-meter and are strongly receiver signal limited. A factor of 5x increase in primary mirror area as proposed in first generation SPOT architecture (and 10x-100x in future generations) will translate into a directly proportional reduction in laser power. The reduction in power also is advantageous to potential receiving systems for Mars communication systems. Our team is currently studying an implementation of this as a potential interface between TDRSS and the Mars based laser system. Both LIDARs and communication receivers have fairly loose wavefront error requirements and limited field-of-view requirements that make these logical initial applications of this technology. Our team has demonstrated well-corrected designs for near-infrared larger field-of-view systems that could replace HST planet imaging capabilities that could serve as a follow-on capability.

The low-cost nature of the primary mirror could enable extremely large systems that cannot be cost-effectively built with aspheric mirrors. Studies of ground based systems and proposals (Hobby Eberly, OWL, ELT) lead us to believe that large (e.g., 25-meter) Spherical Primary solutions may exist with imaging and spectroscopic applications. A major challenge of these systems is overcoming the spherical aberration induced by the spherical primary mirror. There are several potential solutions to this including multiple mirror corrector systems and refractive designs. Our team is also investigating novel designs that make use of novel pupil correction elements

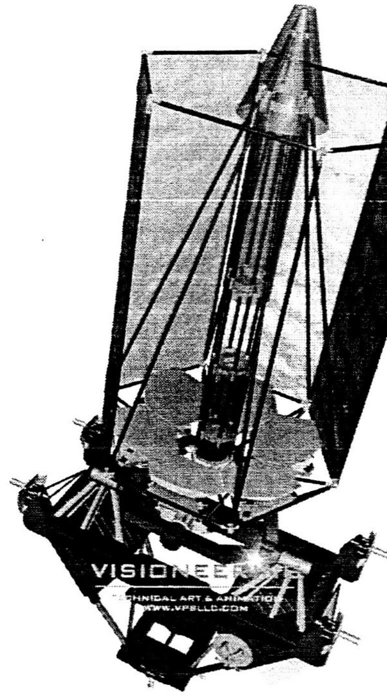
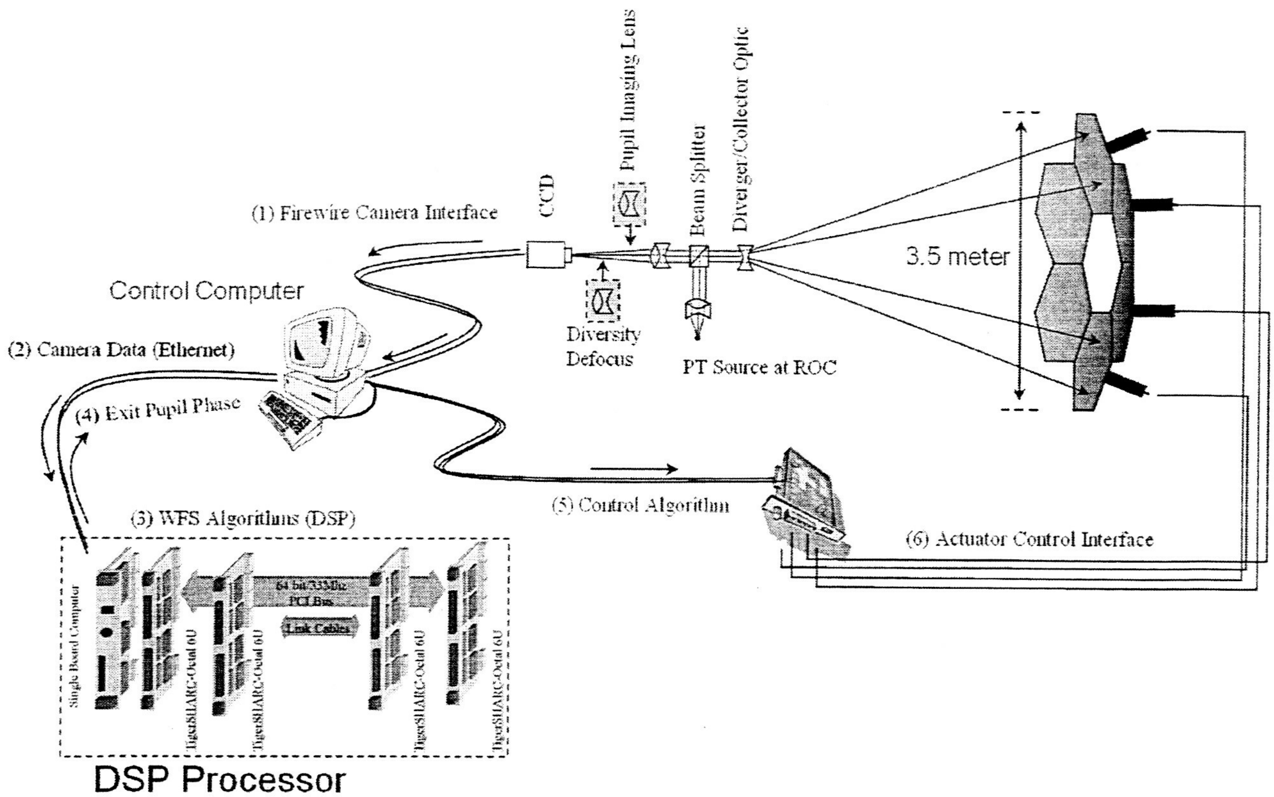


Figure 1 - Early conceptual view of SPOT telescope

3. SPOT Testbed

In order to investigate this architecture, our team is pursuing a testbed funded by internal research and development. We are currently working on the first phase of the testbed, a segmented spherical primary mirror actively phases at center-of-curvature. A diagram of the testbed is shown below.



4. PROGRESS TO DATE

Our team made considerable progress in the design of the testbed, the wavefront sensing and control architecture, and optical design studies. Amongst the key achievements are:

Developed a capability for design and integrated modeling (structural, optical, thermal) of mirror semi-rigid mirror segments that include radius of curvature matching and actuation, gravity sag analysis, thermal stability analysis, and overall performance analysis. We have applied this capability to the design of a casted/replicated mirror segment assembly design. The design makes use of GSFC-developed actuators.

Our team also developed a novel concept for in-situ polishing of the SPOT mirror. The mirror will be tested in-place with a novel RoC metrology setup developed by Co-I Hagopian. Initial polishing of a smaller borosilicate piece along with tooling to support this are in process and being led by co-I Geraldine Wright.

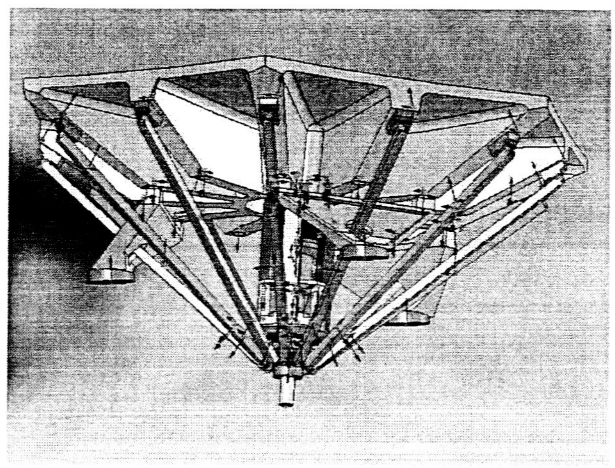


Figure 2 - Recent Design Iteration of the SPOT Mirror Assembly

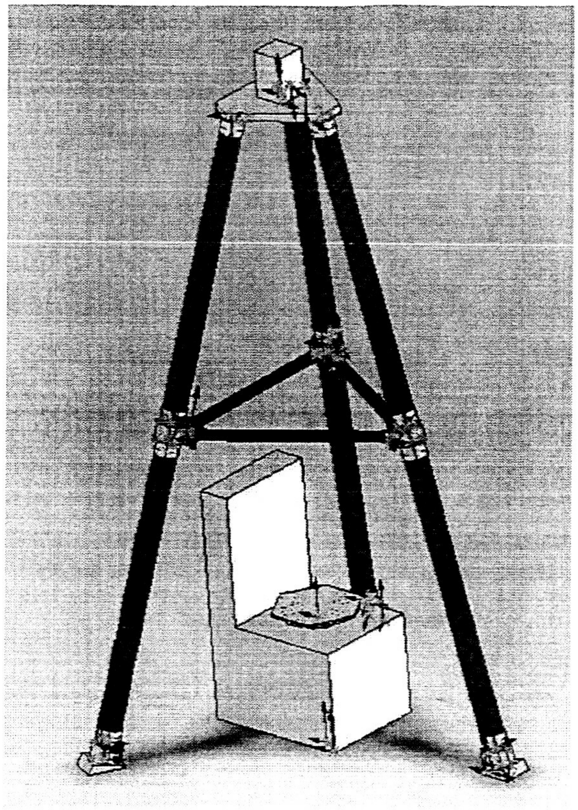


Figure 3 - In-situ mirror segment test setup

Various approaches have been considered for telescope designs for SPOT. Analytic solutions of one and two mirror correctors for the spherical primary have been used, as well as traditional ray-trace based optimization for one, two, and three mirror correctors. Additionally, existing designs in the literature (e.g. HET, OWL) have been considered as starting points for SPOT designs. All three approaches show similar trends: that fewer surfaces for correction require greater aspheric departures on the corrector optics themselves, which seems obvious since the correctors need to compensate for approximately 350 waves (at 1 micron light) of spherical aberration from the primary mirror.

Naturally, the alignment sensitivities are more severe with the one and two corrector aspheres, while a four-mirror corrector has been demonstrated for the Hobby Eberly Telescope. This design work was presented at the Novel Optical Design and Optimization Conference at the SPIE Annual Meeting in Denver, CO, in August of 2004.

Development of techniques, laps, dies, and prototype borosilicate mirrors that serve as the basis for our casted mirror technology. Our team strongly believes that replicated mirror technology such as casted mirrors has the potential to enable a factor of 10-100 cost and schedule savings relative to JWST or HST mirror costs per unit area – a key requisite for a 25-meter architecture.

Development of a supercomputing architecture for image-based wavefront sensing and control. This architecture has been implemented on a desktop network of 32 DSP's (digital signal processors) for a combined performance increase of 3-orders of magnitude (computation time reduced by a factor of 1000). The HDA (Hybrid Diversity Algorithm) has been implemented on the DSP architecture and the current implementation enables quasi-real time wavefront sensing and a demonstration of high-speed control using the novel DSP architecture. A wavefront sensing software protocol has also been developed which allows an ordinary laptop computer to call the DSP's by way of an Ethernet port function call – thus creating a truly compact and portable wavefront sensing and control device. Thirty-two additional DSP's (see Figure 4) are currently being added to the existing 32 (for a total of 64) to establish the additional wavefront sensing bandwidth needed to compensate jitter and other dynamical disturbances at Hz time scales. The technology enables future space telescopes to compensate for thermal stability and greatly reduces the extremely tight mirror-to mirror stability specifications currently facing JWST. As a result, LEO and other mission applications with constantly changing thermal environments can be realized.

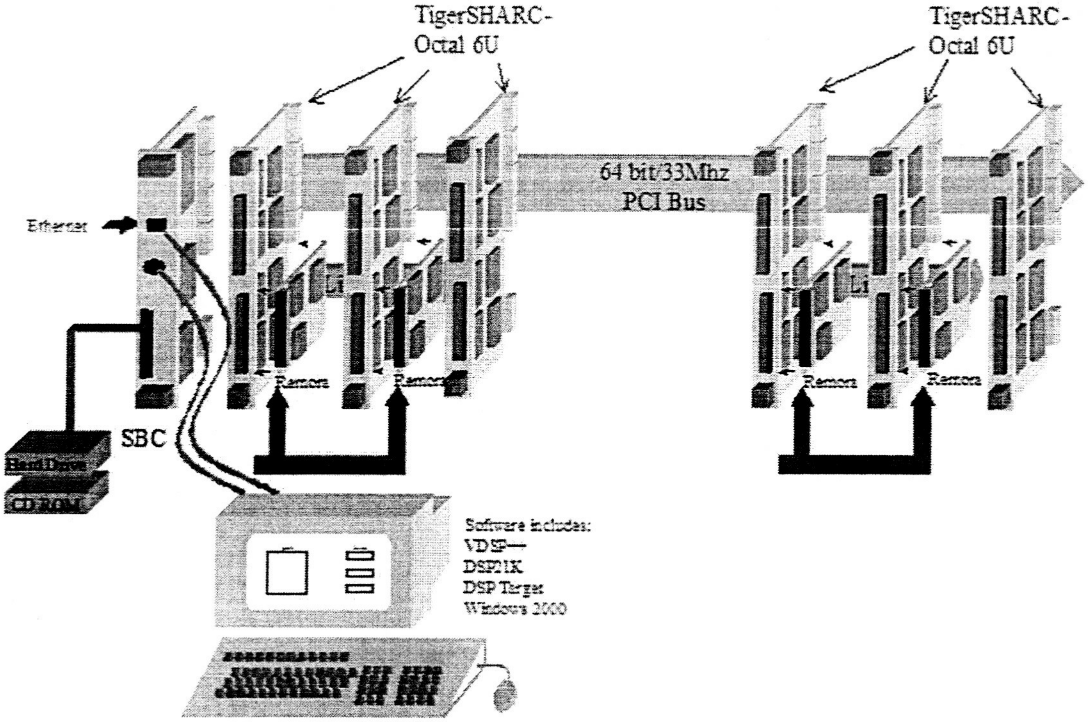


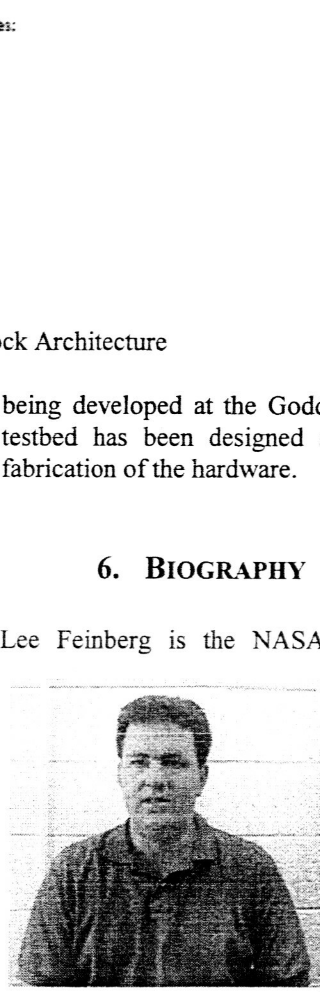
Figure 4 - DSP Block Architecture

Wavefront sensing and control efforts for to date have centered on developing both the DSP hardware and software architectures. Key accomplishments have been the procurement and integration of 4-DSP boards, each with 8 DSP's, which passed floating-point checkout and memory testing. Optimized Fourier transform performance has been obtained in addition to DMA (direct memory access) to enable computational performance at the theoretical maximum of the DSP. Also developed were multi-processor transpose algorithms to enable DSP processing of multiple image data sets. Additional software developments include function calls supporting 100Mbit Ethernet data transfers from a laptop computer to the DSP, and then wavefront sensing results back to the laptop for subsequent display, control, and processing. The function calls have been developed and tested for data sets consisting of 4 – 512 by 512 pixel diversity defocus data sets. Subsequent work in '05 will update the DSP function calls to handle image sizes as large as 2048 by 2048 pixels.

5. CONCLUSION

A proposed architecture for future space telescopes has been described. The architecture addresses the key challenges of current generation systems including an actively controlled primary mirror for easing stability requirements and a cost-effective primary mirror that makes use of replicated mirrors. The architecture is being demonstrated on a testbed being developed at the Goddard Space Flight Center. The testbed has been designed and the team is focusing on fabrication of the hardware.

6. BIOGRAPHY



Lee Feinberg is the NASA Optical Telescope Element Manager for the JWST telescope. In his previous position at NASA, Lee was the Assistant Chief for Technology in the Instrument Technology Center at GSFC. Prior to that, Lee served as acting Instrument Development Office head for the Hubble Space Telescope Project. While on HST, Lee also served as the STIS Instrument Manager and played a key role in the verification of optics and testing of COSTAR and WFPC-2. Lee also led the Conceptual Study Team for the HST Wide Field Camera-3. Before coming to NASA, Lee worked at the University of Rochester's Laboratory for Laser Energetics, at Booz, Allen and Hamilton, and at Ford Aerospace. Lee has a BS in Optics from the University of Rochester and a MS in Applied Physics from The Johns Hopkins University